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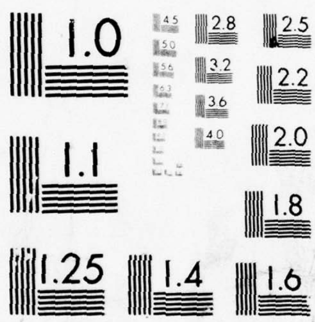

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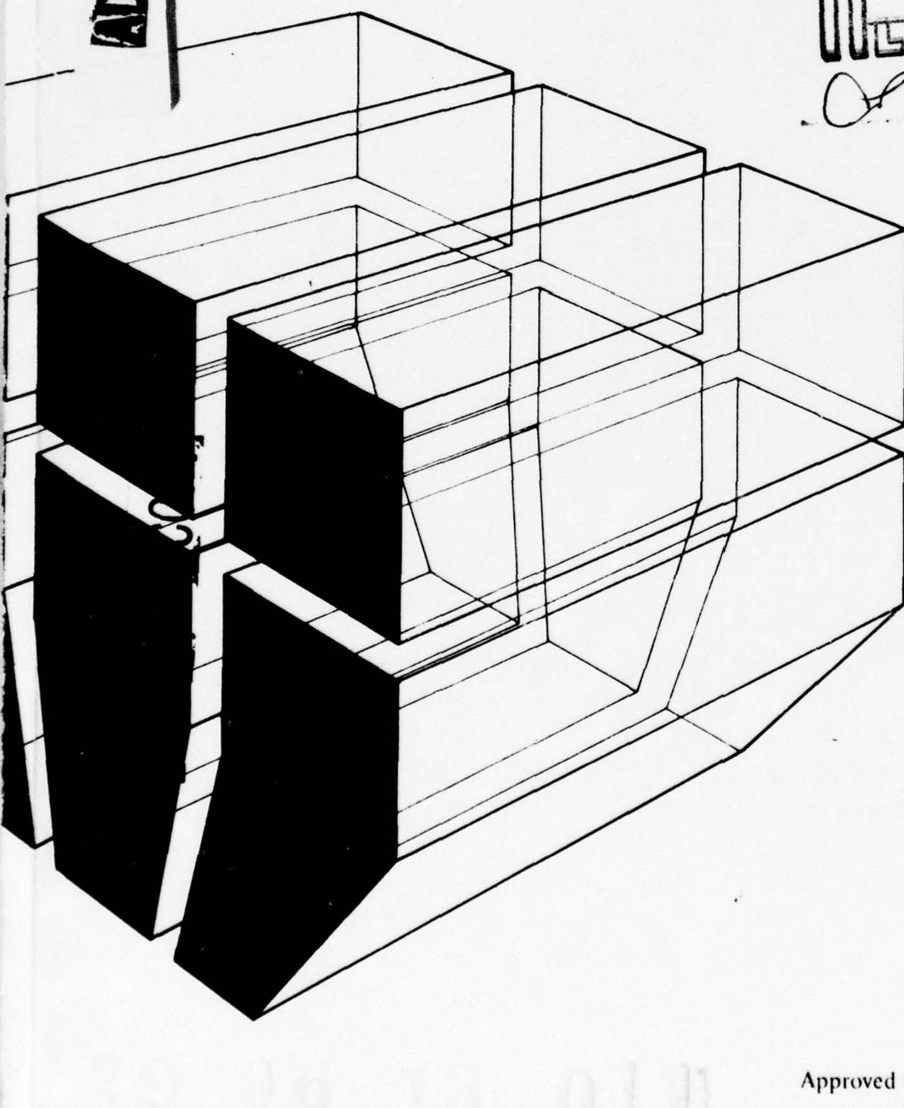
SPECIAL REPORT M-262
May 1979

Applications of Fibrous Shotcrete for Construction in Theater of Operations

INFLATION/FOAM/SHOTCRETE SYSTEM FOR RAPID CONSTRUCTION OF CIRCULAR ARCHES



by
M. Woratzeck

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This study analyzed, designed, and fabricated a semicircular arch structure 32 ft (9.8 m) long by 13 ft (4 m) high using the inflation/foam/shotcrete (IFS) system. Equipment cost, man-hours, skill levels, and time required for construction were monitored.

The test results indicate that the IFS system can be used to construct arch-shaped structures. Skills required to operate the foam and shotcrete equipment are consistent with those available in the Army. Cont

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CONT

The structural failure of the urethane foam arch indicated that creep is a significant factor in the behavior of the polyurethane foam arch and can cause instability and collapse.

FOREWORD

This investigation was conducted by the U.S. Army Construction Engineering Research Laboratory (CERL) for the Directorate of Military Programs, Office of the Chief of Engineers (OCE). The work was performed under Project 4A162719AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Task 8, "Research for Base Development in the Theater of Operations"; Work Unit 001, "Applications of Fibrous Shotcrete for Construction in Theater of Operations." The applicable STO is 77-99.2. The OCE Technical Monitor was G. E. McWhite.

The study was performed by the Engineering and Materials Division (EM). Mr. A. Smith is Principal Investigator, and Dr. G. R. Williamson is Chief of EM.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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INFLATION/FOAM/SHOTCRETE SYSTEM FOR
RAPID CONSTRUCTION OF CIRCULAR ARCHES

1 INTRODUCTION

Background

The concept of inflatable forms for concrete shell construction in the theater of operations (TO) is of significant interest to the Army. Advantages of inflatable forms include the elimination of expensive and elaborate formwork associated with concrete vertical construction, a decrease in construction time, and a reduction in the amount of skilled labor required.

The inflation/foam/shotcrete (IFS) system of contruction has been proven feasible by the U.S. Army Construction Engineering Research Laboratory (CERL).[1] Technical Report M-215 contains a bill of materials, construction procedure, equipment, and test information for the IFS system as applied to hemispherical structures.

This investigation concerns the analysis, design, and fabrication of semicircular arches using the IFS system. The floor plan of the arch-shaped building is rectangular as are most existing Army facilities.

Objective

The objective of this investigation was to develop a system for constructing buildings having rectangular floor plans to the TO using the IFS technique. The system must possess low skill labor requirements.

Approach

A full-sized circular cylindrical shell was fabricated by the IFS system. The building was semicircular in cross section, having a width of 26 ft (7.9 m), a height of 13 ft (4 m) and a length of 32 ft (9.8 m). The building contained a large (10 ft high by 15 ft wide [3 m by 4.5 m]) opening in one end to allow vehicles to enter. Equipment cost, man-hours, skill levels, and time required for construction were noted.

[1] G. R. Williamson, A. Smith, D. Morse, M. Woratzeck, H. Barrett, Inflation/Foam/Shotcrete System for Rapid Shelter Construction, Technical Report M-215/ADA040789 (CERL, May 1977).

Mode of Technology Transfer

The IFS system may be included in TM 5-855-1, Fundamentals of Protective Design (Non-Nuclear),[2] FM 5-15, Field Fortifications,[3] and TM 5-1300, Structures to Resist the Effects of Accidental Explosions.[4]

[2] Protective Design: Fundamentals of Protective Design (Non-Nuclear), TM 5-855-1 (Department of the Army [DA], 19 July 1965).
[3] Field Fortifications, FM 5-15 (DA, 27 June 1972).
[4] Structures to Resist the Effects of Accidental Explosions, TM 5-1300 (DA, 15 July 1969).

2 ANALYSIS OF IFS ARCH STRUCTURE

Problem

A full-scale structure having a rectangular floor plan was to be constructed to demonstrate the IFS system's applicability to building shapes other than spherical and floor plans other than circular. The structure was to have enough floor space and overhead clearance to serve as a barracks or other small Army facility. The building was to be 20 ft (6.1 m) wide and 32 ft (9.8 m) long, with a minimum 8 ft (2.4 m) overhead clearance.

Shape Selection

Having established the structure's interior dimensions, the shape of inflatable membrane which would most suitably act as a form to provide this space was to be selected. The inflatable membrane system had the following requirements:

1. It had to be light enough to be carried and positioned by a few persons

2. It had to be simple to erect

3. The resulting shape had to use floor space as fully as possible

4. The shape had to be structurally efficient to avoid the need for excessive foam thickness or elaborate bracing and reinforcing of the foam form against the dead weight of the plastic shotcrete

5. The shape had to allow a large opening for vehicles or equipment to pass through.

The inflation characteristics of a lightweight plastic membrane limit it to two inflated shapes: spherical and cylindrical. The inflatable membrane used for this project was to be either cylindrical or a combination of cylindrical and spherical.

Initial feasibility tests were conducted using a half-scale model to determine if a vertical walled-pitched roof structure could be produced from multiple inflatable cylinders. Three cylinders were inflated and covered with a sheet of plastic (Figure 1). The model was 10 ft (3.0 m) wide, 20 ft (6.1 m) long and 6 ft (1.8 m) high, and had vertical walls. However, two deficiencies were apparent. First, the weight of the foam caused the plastic cover sheet to sag between cylinders (Figure 2). This problem would worsen considerably in a full-scale model, which would have a greater unsupported length of cover sheet. Second, the

Figure 1. Multiple tube membrane with cover sheet.

Figure 2. Foam structure produced from multiple tube membrane. Note sag and flatness of roof.

weight of the fresh shotcrete causes bending moments across the roof that are large relative to the strength of the foam, thus requiring an excessive thickness of foam or some form of reinforcement. Therefore, although the model provided economical use of floor space, it was not structurally efficient.

Based on the initial test results, a semicircular cylindrical arch with vertical end walls was selected as the shape to be evaluated. This design satisfied each of the previously stated requirements except full use of floor space.

To obtain a 20-ft (6.1-m)-wide area with a minimum of 8-ft (2.4-m) clearance in a semicircular arch, a total width of 26 ft (7.9 m) is required. Twenty-three percent of the total floor area is "unusable." Although the additional width requirement is a drawback of the circular cross section, with proper planning the "unusable" area can be used. If the clearance criterion is reduced to 6 ft (1.8 m), only 11 percent of the floor space is unusable. Objects such as beds, workbenches, certain shop equipment, and filing cabinets, which do not require an 8-ft (2.4-m) clearance, may be placed against the side walls, increasing the total usable floor space.

Design of Foam and Shotcrete Arch

Design Criteria

The completed arch structure must carry its own dead load plus wind and snow loads and, if used in a TO, may be required to have ballistics resistance. The arch thickness will be controlled by one of the above requirements, depending on its intended use.

Table 1 shows the dead, wind, and snow loads used in the design of the arch structure.

Ballistics tests performed previously[5] indicated that 3 in. (0.76 m) of steel fibrous shotcrete can offer the protection shown in Table 2. This is an acceptable thickness when designing for ballistics protection from small arms fire.

[5] D. J. Naus and G. R. Williamson, Ballistics Tests of Fibrous Concrete Dome and Plate Specimens, Technical Report M-179/ADA025209 (CERL, April 1976).

Table 1

Complete Arch Loads

Dead Load	Live Load
Dead load (W_D) depends on the foam and shotcrete thickness, and foam density.	Snow load (W_S) is a uniform load of 15 lb/sq ft (718 Pa) over the projected area of the arch
	Wind load (W_W) is a positive pressure on the windward side and negative pressure on the leeward side of 40/lb sq ft (1915 Pa) (100 mph wind)(160.9 km/hr)

Table 2

Ballistic Resistance of 3-In. (.076-m)-Thick Steel Fiber Shotcrete

Complete Protection From:

Weapon	Range
M67 hand grenade	5 ft (1.5 m)
81 mm mortar	15 ft (4.6 m)
M16 rifle, Ball ammo, M193, 5.66 mm	50 yd (45.7 m)
M73 30 caliber machine gun, Ball ammo, M80, 7.62 mm 45-caliber pistol	50 yd (45.7 m)
Ball ammo, M191	10 yd (9.1 m)

The foam arch may be subjected to three sets of loading conditions. First, local buckling may result from the pressure of the shotcrete on the foam surface. Previous tests have indicated that 3 in. (.076 m) of foam can resist this type of buckling.[6] The other two loading conditions are various combinations of dead plus live loads. If the shotcrete is to be applied immediately (Condition 1), the foam arch must carry the loads listed in Table 3.

Table 3

Foam Arch Loads for Condition 1

Dead Load	Live Load
Dead load (W_D) depends on the foam thickness and density and shotcrete thickness	Wind load (W_W), is a positive pressure on the windward side and negative pressure on the leeward side of 10 lb/sq ft (4780 Pa) (50 mph wind)(80.5)

If the foam arch is to stand on its own for more than a few weeks before shotcreting (Condition 2), or if a delay in shotcreting is likely, it must be able to carry the loads in Table 1, except that the snow load should not be superimposed with the shotcrete dead weight. The design is based on whichever of Conditions 1 or 2 requires the greater foam thickness, assuming the initial buckling criteria have been met.

If the foam arch is to be used as a foam structure alone (Condition 3), it must be designed to carry the loads in Table 1 except that of the shotcrete deadweight.

If IFS arch was to be shotcreted 1 day after the completion of the foam work. However, since a further delay was possible, Conditions 1 and 2 were both checked.

Foam and Shotcrete Shell Design

The "Membrane Theory"[7] was used to analyze the foam and shotcrete arches as thin, semicircular cylindrical shells supported by vertical

[6] G. R. Williamson, et al., Inflation/Foam/Shotcrete System for Rapid Construction, Technical Report M-215/ADA040789 (CERL, May 1977).
[7] A. Pfluger, Elementary Statics of Shells (McGraw-Hill, 1961), p. 116.

end diaphragms. An arch thickness-to-radius ratio of less than 1/20 allows the use of this theory with an error of less than 5 percent.[8] Thus, the theory will introduce an analytical error of less than 5 percent if the foam plus shotcrete thickness does not exceed 7.8 in. (.198 m) for the 26-ft (7.9-m)-diameter arch.

Appendix B gives membrane equations, locations and magnitude of maximum stress, and deflections. In summary, less than 1 in. (25.4 mm) of shotcrete is required to resist the loads in Table 1; thus the 3-in. (0.76-mm) thickness required for ballistics resistance controlled the design. The foam shell was then analyzed under loading Conditions 1 and 2 assuming a shotcrete thickness of 3 in. (.076 m) (Appendix B). Here the dead weight of the foam and shotcrete controlled the design and a foam thickness of 4 in. (.101 m) was found adequate. Including a safety factor of 1.5 to compensate for difficulties in controlling the foam thickness, the final design thickness of the foam was 6 in. (1.8 m). This was twice the thickness required to prevent local buckling during shotcreting.

Analysis and Design of Inflatable Form[9]

A single-walled, semicircular arch with an enclosed bottom was selected as the type of inflatable form to be used. This was chosen over a dual-walled inflatable form for two reasons. First, it contains a greater volume of enclosed air. If anything went wrong with the air supply, the single-walled form could carry the weight of the foam longer, allowing more time for repair or replacement of the air supply. Second, the dual-walled system requires more pressure, thus making small leaks a greater problem. Since foaming is not practical in wind velocities exceeding 20 mph (32 km/hr) or during rain and snow, the inflatable form needs only to carry its own weight, the weight of the foam, and the 20 mph (32 km/hr) wind load.*

The dead weight of 6 in. (1.8 m) of 2.5 lb sq ft (119.7 Pa) polyurethane foam plus the weight of the inflatable form is 1.35 lb/sq ft (64.6 Pa).

Wind Load

To resist folding caused by wind load, the internal pressure, P_{iw}, of the inflated form must equal or exceed the wind pressure loading, P_w.

[8] E. Baker, L. Kovalevsky, F. Rish, Structural Analysis of Shells (McGraw-Hill, 1972), p. 27.

[9] Roger N. Dent, Principles of Pneumatic Architecture (William Clowes & Sons, Ltd., 1972), pp 51-84.

* Foaming in wind velocities exceeding 20 mph (32 km/hr) is extremely difficult because severe drifting of the foam mist causes overspray and waste. Foaming during inclement weather is not advised since water inhibits the chemical reaction of the urethane foam.

$$P_{iw} \geq P_w$$

The wind pressure is

$$P_w = CQ$$

where C = aerodynamic coefficient (0.65 for semicircular forms)

Q = dynamic pressure ($Q = 1/2\ pv^2$@p = density of air = 0.0765 lb/cu ft/32.2 ft/sec^2)

v = wind velocity = 20 mph = 29.3 ft/sec

Thus: $P_{iw} \geq CQ = 0.65\ Q = 0.325\ pv^2$

$P_{iw} \geq .664$ lb/cu ft = .0046 lb/sq in. (31.7 Pa)

Dead Weight (Membrane and Foam)

To prevent folding caused by dead weight (membrane plus foam), g, the internal pressure, P_{ig}, must equal or exceed the dead weight.

$$P_{ig} \geq g$$

If g = 1.35 lb/sq ft = 0.01 lb/sq in.

$P_{ig} \geq 0.01$ lb/sq in. (68.9 Pa)

Combined Loads and Safety Factors

The internal pressure required to resist combined wind and dead loads, P_i is:

$$P_i = P_{iw} + P_{ig}$$

$$P_i = 0.01 + 0.0046$$

$P_i = .0146$ lb/sq in. (100.6 Pa)

Analyzing a safety factor (SF) of 1.5, the actual minimum internal pressure is

$P_{isf} = 1.5\ (0.0145) = 0.022$ lb/sq in. (151.7 Pa)

Maximum Pressure

The maximum inflation pressure, P_{im}, is that pressure which causes a membrane load per unit length equal to that of the strength of the membrane material. When the only load applied to the membrane is its own dead weight, P_{gm}, the maximum membrane load per unit length, T_m, is given by:

$$T_m = (P_{im} - P_{gm})R$$

Where R = radius.

The membrane material, .008-in. (0.20-mm)-thick reinforced polyethylene sheet, has a tensile strength of 35 lb/in. Thus,

$$P_{im} = (T/R + P_{gm})$$

Where R = 13 ft = 156 in.

P_{gm} = .0007 lb/sq in.

P_{im} = *35 lb/sq in./156 in. + 0.0007 lb/sq in.*

P_{im} = 0.23 lb/sq in. (1586 Pa).

The internal pressure must not exceed 0.23 lb/sq in. (1586 Pa) to prevent failure of the membrane material.

Tie-Down Analysis

The bottom portion of the inflatable form exerts a pressure equal to that of the design inflation pressure, P_{isF}, on the projected area, A, of the circular cylinder. The resulting uplift force, Fu, is given by:

$$Fu = P_{isF}\,A$$

$$A = 832 \text{ sq ft}$$

$$P_{isF} = .022 \text{ psi} = 3.168 \text{ lb/sq ft}$$

$$Fu = 2636 \text{ lb } (1198 \text{ kg}).$$

This force must be resisted by a tie-down mechanism.

Figure 3 illustrates the tie-down mechanism used for the semicircular arch inflatable membrane. The system consists of 62 stakes made from No. 6 steel reinforcing bars (Figure 4) with 2.5-in. (63.5-mm)-inside-diameter eyes at one end. The stakes are driven roughly 2 ft (.61 m) into the ground so that the eyes are at ground level at 2-ft (.61-m) intervals along the base of the inflatable form. A 1-in. (25.4-mm)-inside-diameter Schedule 80 PVC pipe is passed through a pocket sewn onto the base of the membrane. The pocket has 6-in. (.152-m) openings every 2 ft (.61 m) to allow the pipe to pass through the eyes in the stakes.

It should be noted that this type of tie-down system is not reusable. The plastic pipe and stakes, which cost $200, are not recoverable. Although the anchor pockets on the inflatable form used in the CERL demonstration were not detachable and were cut away to remove the inflatable form, the anchor pockets of field-developed inflatable forms would be detachable and spare pockets would be supplied.

Tnis type of tie-down mechanism is suitable for ground conditions that allow the use of stakes that are long enough to resist the uplift force. Rocky or extremely wet ground would require a different type of tiedown, such as a 6-in. by 6-in. (.152-m by .152-m) concrete beam with steel rings imbedded at appropriate intervals. The beam could be prepoured the day before use.

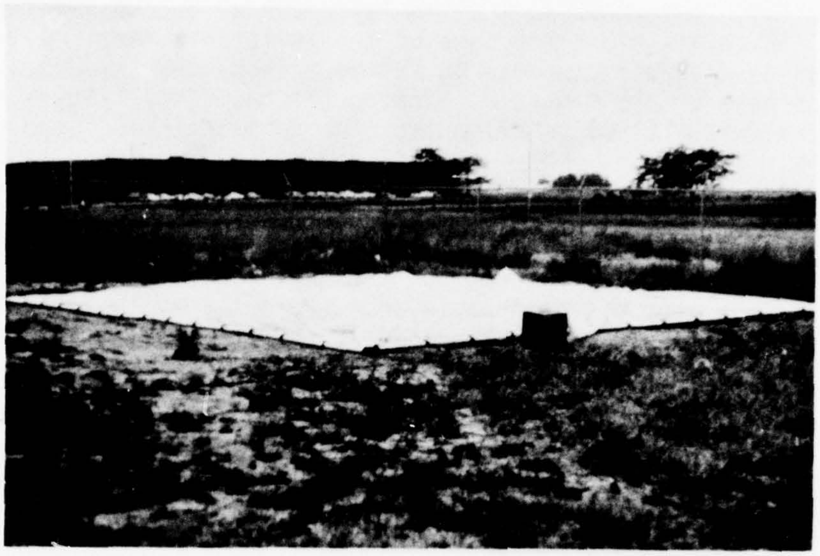


Figure 3. Membrane tie-down mechanism.

Figure 4. Detail of stakes and PVC pipe used as membrane tie-downs.

3 EQUIPMENT AND MATERIALS

Equipment

The equipment used to construct the IFS arch is the same as that used for the IFS domes; the equipment list and associated costs in Technical Report M-215 are also applicable to this study. The only additional item of equipment is the fiber feeder shown in Figure 5, which was used to incorporate fibers into the mix.

Materials

Most of the materials used to construct the IFS arch are the same as those used for the IFS dome, as described in Technical Report M-215. The additional materials used in the tie-down device are:

1. 1-in. (25-mm)-ID Schedule 80 PVC pipe, \$78.80/100 ft (30.5 m)

2. 3/4-in. (19-mm)-diameter (No. 6) steel reinforcing bar, any grade, \$0.20/lb (.44 kg)

The polyurethane foam used has a density of 2.5 lb/cu ft (40 kg/m^3) and will attain the following properties after 24 hours:

Tensile strength (perpendicular to foam rise) = 70 lb/sq in. (482.6 kPa)

Modulus of elasticity in tension (perpendicular to foam rise) = 150 lb/sq in. (1.03 MPa)

Compressive strength (perpendicular to foam rise) = 40 lb/sq in. (275 kPa)

Modulus of elasticity in compression (perpendicular to foam rise) = 1000 lb/sq in. (6.89 GPa)

Flexural strength (perpendicular to foam rise) = 50 lb/sq in. (344.7 kPa)

"K" factor 0.12 Btu/hr sq ft (°F/in.)[10]

It is recommended that this type of foam be sprayed onto surfaces having temperatures greater than 45°F (7°C). It can be sprayed on cooler surfaces but will result in a thin, dense layer of polyurethane adjacent to the surface, which requires slightly more material.

[10] Urethane Resins for Spray Application (Freeman Chemical Corporation, January 1972).

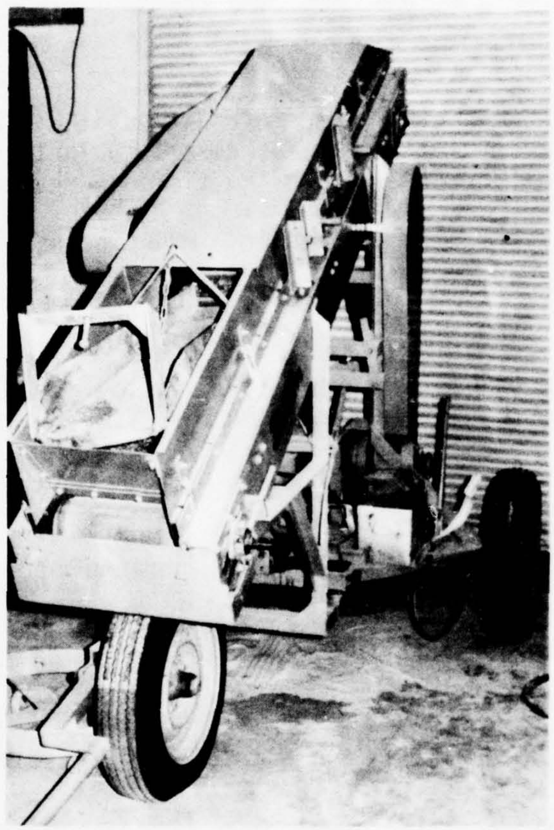


Figure 5. Fiber Feeder.

A recommended shotcrete design mix per cubic yard (cubic meter) is as follows:

Cement - 890 lb (530 kg)

Torpedo sand - 2600 lb (1540 kg)

Steel fibers - 180 lb (105 kg)

Water - as required

This design mix will produce concrete with 28-day properties as follows:

Compressive strength = 6000 lb/sq in. (41.4 GPa)

Splitting tensile strength = 900 lb/sq in. (6.2 GPa)

Flexural strength = 1100 lb/sq in. (7.6 GPa)

Modulus of elasticity = 3.8×10^6 lb/sq in. (2.62×10^{10} Pa)

4 PROCEDURE

The procedure for using the IFS system to construct arch-type shelters is as follows:

1. Obtain inflatable forms for the size and shape of structure desired.

2. Obtain steel stakes and pipe for tie-down mechanism. If soil conditions do not permit use of stakes, a concrete beam or floor slab can be used as a tie-down, but will have to set for 1 day before foaming can begin.

3. Attach the inflatable form to the tie-down device (Figure 3).

4. Attach the air blower and inflate the form. This process takes 2 hours for a 26-ft (7.9-m)-diameter by 32-ft (9.8-m)-long arch using a 40 cu ft/min (1.13 m^3/min) blower. Safety ropes must be used to keep the form under control during inflation (Figure 6) since a gentle breeze can cause the partially inflated form to behave as a sail. When the form is fully inflated the safety ropes may be removed.

5. After inflation, make a simple manometer consisting of a flexible plastic tube approximately 1/2 in. (12.7 mm) in diameter bent into a U-shape. Fill the tube with water to approximately 1 ft (0.3 m) above the bottom of the U. Cut a small hole into the membrane where an opening in the structure is planned, and insert one end of the manometer. Leave the other end exposed to the atmosphere. The difference in water levels, Λh, is measured and related to the internal pressure P_i by:

$$P_i = 0.036 \Lambda$$

where Λh is in inches and P_i in lb/sq in. or:

$$P_i = \Lambda h$$

where Λh is in centimeters and P_i in gr/cm^2.

The blower must be capable of maintaining the minimum air pressure. The pressure should be maintained close to the design pressure, which can be accomplished in many ways. Two possibilities are as follows:

a. The blower intake opening size can be adjusted while the pressure is monitored with a manometer.

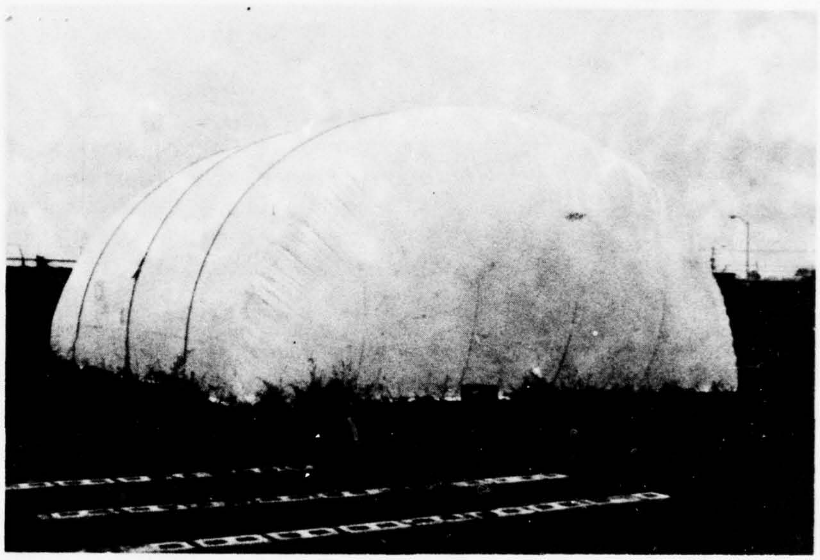


Figure 6. Inflatable form showing safety ropes.

b. An exhaust tube having the same diameter as the blower hose and an adjustable opening can be attached to the inflatable form and adjusted while the pressure is monitored with a manometer. The pressure should be checked hourly during foaming and adjusted as necessary.

6. Apply polyurethane foam to the required thickness (Figure 7) for the size and shape of the building. A round-tipped 1/4-in. (6.35-mm)-diameter steel rod marked with the desired foam thickness can be used to check the thickness periodically.

7. Create openings in the structure by placing forms against the inflatable form and foaming them into place (Figure 8).

8. Leave the form inflated 24 hours to allow complete polymerization of the foam.

9. Apply shotcrete to the desired thickness (Figure 9), depending on the size and purpose of the structure. (Shotcreting should be delayed until the day following completion of the foam work to ensure that the foam has attained full strength.) As a guide in controlling the shotcrete thickness, insert a piece of 12-gauge wire into the foam so that the length of the projected wire is equal to the shotcrete thickness required.

10. Use the same curing procedures for concrete placed by the shotcreting process as for ordinary concrete.

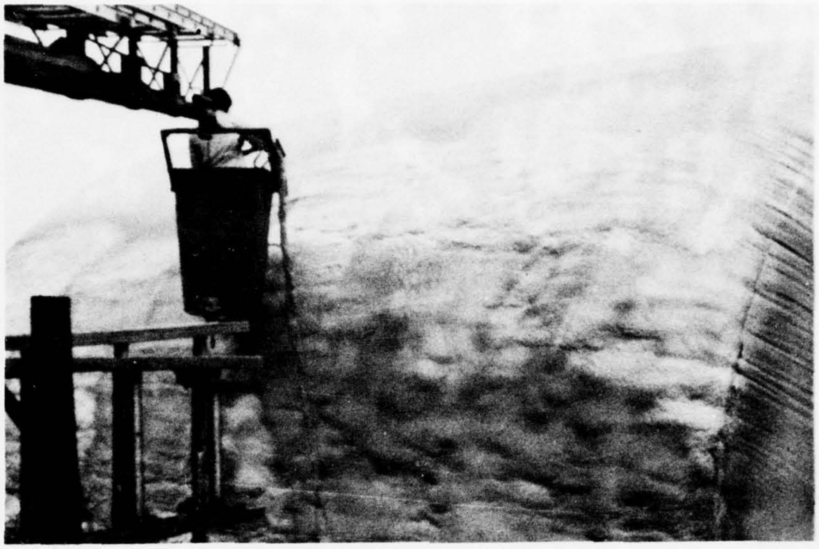


Figure 7. Application of polyurethane foam.

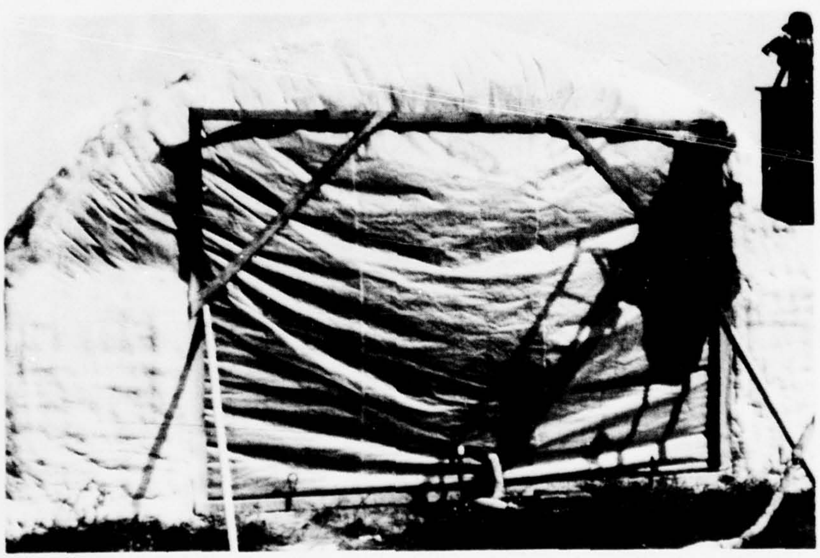


Figure 8. Foaming door frame into place.

Figure 9. Application of shotcrete.

5 RESULTS AND DISCUSSION

Arch Construction

One full-scale 26-ft (7.9-m)-diameter, 32-ft (9.8-m)-long, circular IFS arch was constructed at CERL. The inflatable form was attached to the tie-down mechanism by two men in 8 hours. The form was fully inflated in 2 hours. Three men applied 6 in. (.152 mm) of foam to the form in 11 hours using a single spray gun.

Although the 6-in. (.152-m)-thick foam arch was designed in conjunction with a 3-in. (.076-m)-thick layer of plastic shotcrete, the shotcrete was actually applied in a thin layer varying from 1/2 to 1 in. (12.7 to 25.4 mm). It was decided that this thickness would protect the exterior foam surface and allow the foam arch building to be studied as a temporary structure. The foam arch's ability to resist wind and snow loading and the effects of cold weather would be determined. After such studies the remaining shotcrete would be added.

Three men completed the shotcreting in 10 hours. A ready mix transit mixer delivered a 7-cu-yd (.2-m^3) load of dry-mixed concrete with the steel fibers incorporated, which was discharged on the ground. A frontend loader was used to fill a hopper, which was then elevated above the shotcrete machine by fork lift (Figure 10). (One man operated both machines.) The material flowed into the shotcrete machine, where the nozzleman controlled the addition of water and thickness of the shotcrete. Work above the 6 ft (1.8 m) level was done from a bucket crane operated by a third man (Figure 11). After completion of the arch the inflatable form was removed.

Field Demonstration

The simplicity of the IFS technique was demonstrated during construction of the arches. Local members of the 2nd Bn, 130th Infantry, and Company "B," 747 Maintenance Bn, National Guard, who had no prior experience with either the foam or shotcrete equipment, were taught to operate it after less than 1 hour (Figures 12 and 13). The troops had no problems understanding or operating either piece of equipment.

Failure

Cracks became visible in the shotcrete layer during the week following completion of the arch. It was evident that in some places there was barely enough shotcrete to cover the foam. The shotcrete layer was not contributing to the strength or stiffness of the arch but was adding dead weight to the foam structure.

Figure 10. Hopper positioned above shotcrete machine.

Figure 11. Shotcreting from bucket crane.

Figure 12. National Guardsman spraying foam.

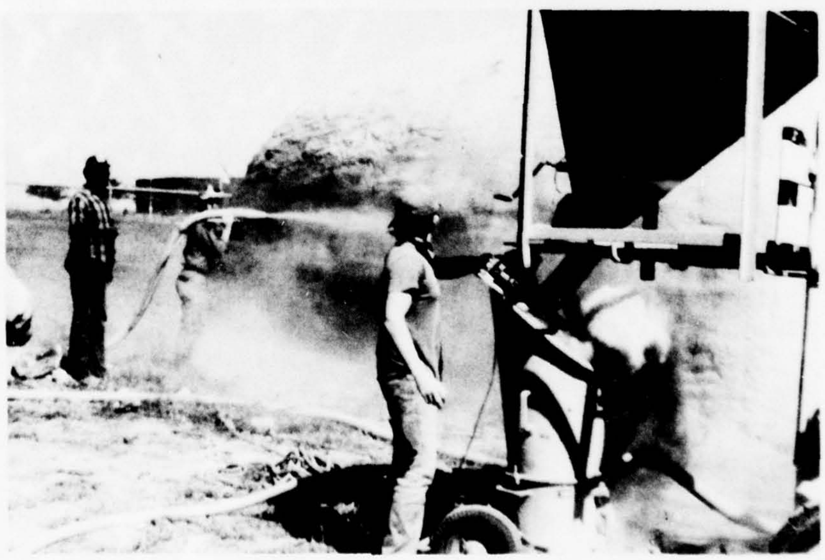


Figure 13. National Guardsman spraying shotcrete.

Six days after completion, the roof of the arch was sagging visibly. There was no attempt to stop the sagging, in order to determine whether it would continue. By 3 weeks after completion of the arch, the roof had dropped 4 ft (1.2 m) from its original height of 13 ft (4 m) (Figure 14). Rainwater began ponding in the center, and 1 week later the roof had dropped an additional 0.5 ft (.15 m) (Figure 15). Four days later it collapsed (Figure 16).

The slow change in shape of the arch indicated that creep in the foam initiated the failure. Circular arches are efficient structural shapes and are normally subjected only to membrane stresses. As the arch deflected, however, the internal forces changed from membrane to flexural. The flexural forces increased as deformation continued, becoming significantly larger than the original membrane stresses until failure occurred.

A section of foam cut from the collapsed arch was used to assess the foam's creep properties. A 4-in. by 4-in. by 30-in. (.1-m by .1-m by .8-m) beam was loaded with a dead weight of 9 lb (4.1 kg) applied at each third point as shown in Figure 17. This arrangement applied an extreme fiber stress of 7.5 lb/sq in. (51.7 kPa) in the center third of the beam. The resulting time-dependent deflection curve is shown in Figure 18. The initial deflection tripled in less than 5 days.

If an effective modulus of elasticity (Ec) incorporating both elastic and creep strains is used to compute the foam arch deflection, the resulting deflections are inversely proportional to Ec (Appendix B). The inverse of Ec and the deflection of the arch with respect to time for a constant load is similar to Figure 18. Thus it appears that the resulting time-dependent deflection at a constant load for the foam arch was large enough to cause the internal stresses to change from membrane to the more severe flexural stresses.

The failure of the arch indicates that large foam arches without structural shotcrete need to be stiffened if they are long-term load carrying members. Stiffening can be achieved with either a horizontal ridge beam and columns or tensional cross bracing in the plane of the arch. Until further tests are conducted, unstiffened foam arches without structural shotcrete should not be considered for field application. Also, stiffening may be required during the placement and curing of the shotcrete. This stiffening requirement needs further analysis and testing.

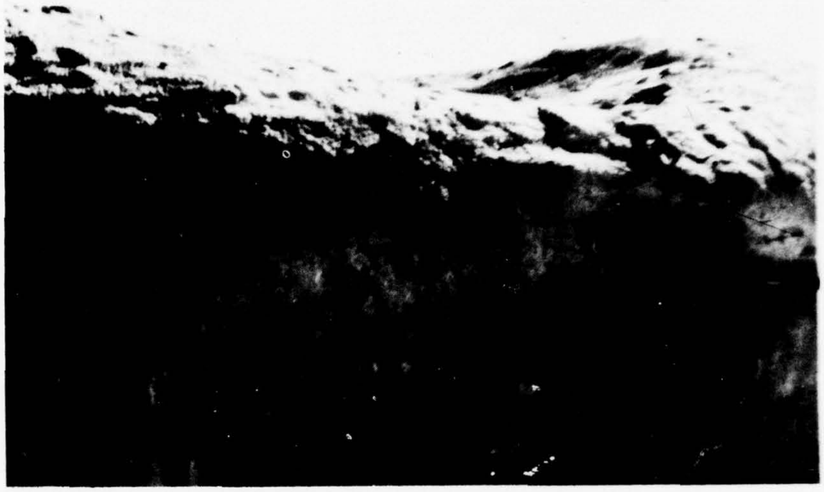


Figure 14. Arch sag 3 weeks after completion.

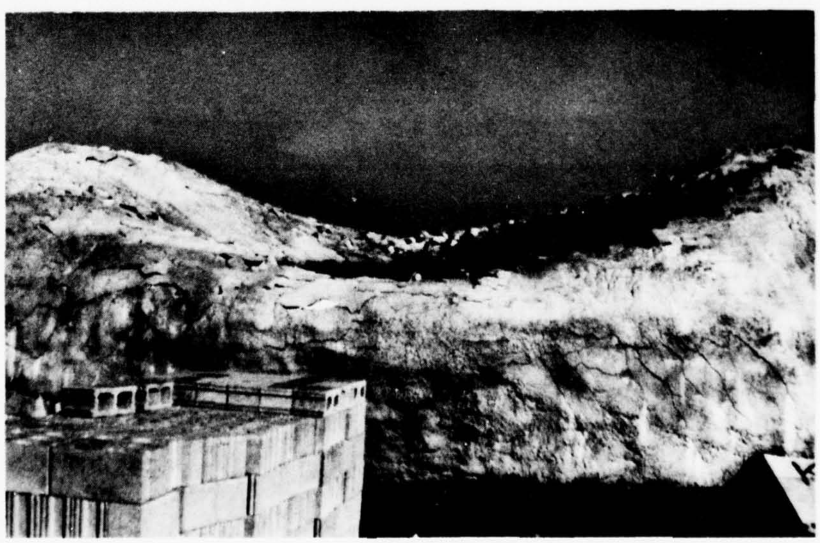


Figure 15. Arch sag after ponding of water.

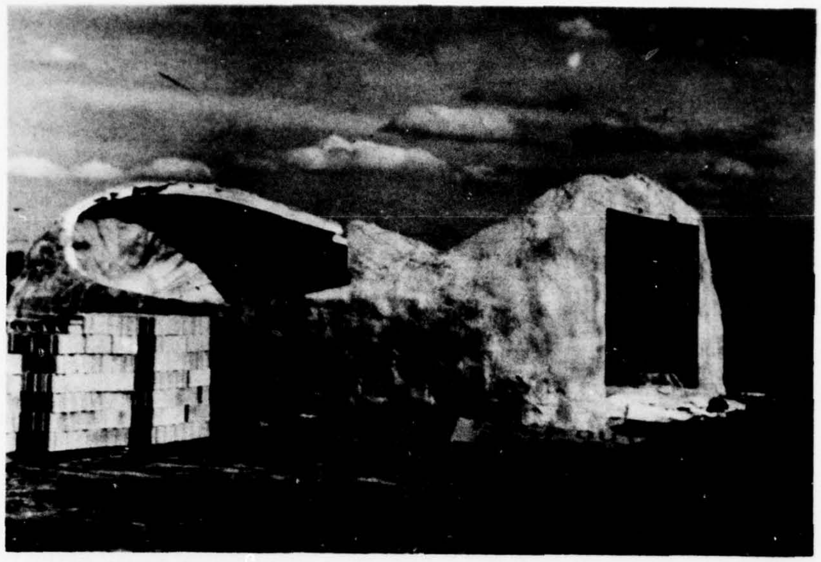


Figure 16. Collapsed arch 5 weeks after completion.

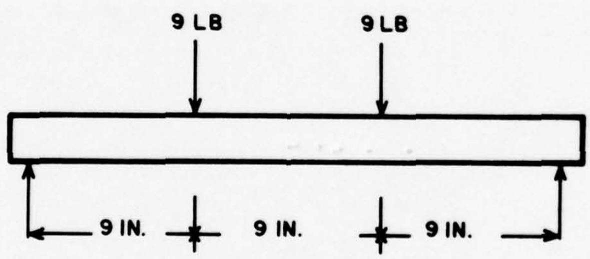


Figure 17. Diagram of foam creep test.

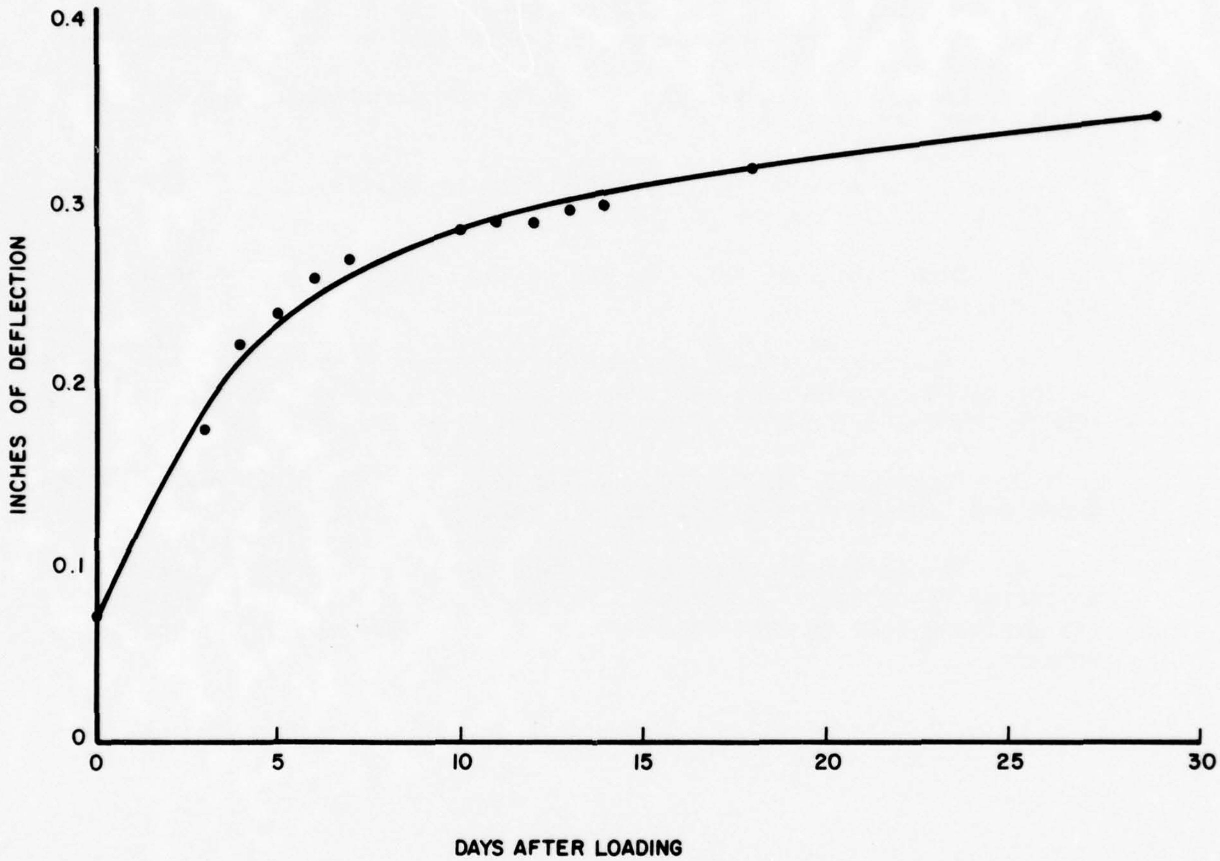


Figure 18. Time-deflection curve for foam beam.

6 CONCLUSIONS AND RECOMMENDATIONS

It is concluded that:

1. The IFS System can be used to construct arch-shaped rectangular structures.

2. The skill level required to operate the equipment used in constructing the IFS system is consistent with that available in the Army.

3. Creep is a significant factor in the structural behavior of polyurethane foam arches.

Before the non-dome-shaped IFS system technology is transferred to the field, it is recommended that:

1. More extensive tests be run on the creep properties of polyurethane foam.

2. Fiberglass, insect screening, and other forms of reinforcing be investigated to determine how they might be applied to the IFS system to reduce creep and increase strength of the polyurethane foam.

3. Techniques for stiffening foam arches, such as horizontal ridge beams and tensional cross bracing, be analyzed and tested.

4. The inflatable form be modified to be capable of supporting the weight of the plastic shotcrete. This would reduce the thickness of polyurethane foam to that required for insulation and inhibit shotcrete rebound.

APPENDIX A: MATERIAL SUPPLIERS

Equipment and material used in this study were purchased from the following suppliers. All the items are also available from other manufacturers.

SHOTCRETE:

Reed Guncrete Equipment

Halco Incorporated
Conquip Division
3005 N. 7th Street & Trafficway
Kansas City, KS 66115
Contact: Mr. Hal Kalousek

Steel Fibers

U.S. Steel
600 Grant Street
Pittsburgh, PA 15230
Contact: Mr. Richard Pfister

FOAM:

Gusmer Spray Equipment (Model FF)

Gusmer Corporation
Route 18 and Spring Valley Road
Old Bridge, NY 08857
Contact: Mr. Paul White

Foam Material System (2.5 lb/cu ft polyurethane)

CPR Division Upjohn
555 Alaska Avenue
Torrance, CA 90503

MEMBRANE: NONELASTIC

Reinforced Polyethelene (Loretex)

American Bleached Goods
Division of Chane and Earley Inc.
1460 Broadway
New York, NY 10036
Contact: Mr. Don Wilmarth

MOLD RELEASE

Brulin Sp 169
Brulin & Co., Inc.
P.O. Box 270-B
Indianapolis, IN 46206

APPENDIX B:

STRUCTURAL ANALYSIS AND DESIGN OF CYLINDRICAL ARCH USING MEMBRANE THEORY

STRUCTURAL PROPERTIES OF POLYURETHANE FOAM

y_f = Density = 2.5 lb/cu ft (40 kg/m^3)

f_{ft} = Tensile strength = 70 lb/sq in. (482.6 kPa)

E_{ft} = Elastic modulus in tension = 150 lb/sq in. (1034.2 kPa)

f_{fc} = Compressive strength = 40 lb/sq in. (275.8 kPa)

E_{fc} = Elastic modulus in compression = 1000 lb/sq in. (6894.7 kPa)

f_{fv} = Shear strength - 30 lb/sq in. (206.8 kPa)

f_{ff} = Flexural strength - 50 lb/sq in. (344.7 kPa)

ν_{fc} = Poisson's ratio = 0.10

f_{cv} = Shear strength = $0.2f_{cc}$ = $\pm$ 1200 lb/sq in. (8273.7 kPa)

STRUCTURAL PROPERTIES OF STEEL FIBROUS SHOTCRETE

λ_c = Density = 150 lb/cu ft (2403 kg/m^3)

f_{cc} = Compressive strength = 6000 lb/sq in. (41368.5 kPa)

f_{ct} = Splitting tensile strength = 900 lb/sq in. (6205.3 kPa)

f_{cf} = Flexural strength = 1100 lb/sq in. (7584.2 kPa)

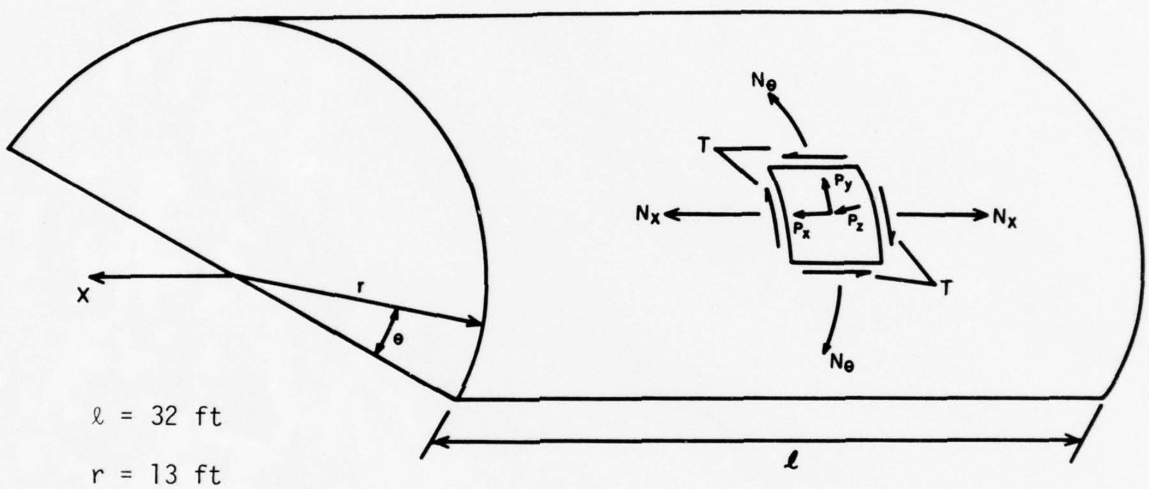
E_c = Modulus of elasticity = 3.8×10^6 lb/sq in. (2.62×10^{10}Pa)

ν_c = Poisson's ratio = 0.15

f_{cv} = Shear strength = $0.2f_{cc}$ = $\pm$ 1200 lb/sq in. (8273.7 kPa)

SECTIONAL LOAD FORMULAE FOR ARCH

(Refer to Figure B1)



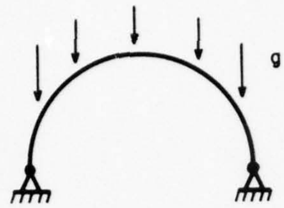
ℓ = 32 ft

r = 13 ft

Arch is assumed pinned and supported about its bottom edge.

Figure B1. Sign convention and nomenclature for loads and forces.

Dead Weight Loading



$P_y = -g \cos\theta$

$P_z = \ g \sin\theta$

Where g is the weight per unit area of the arch surface.

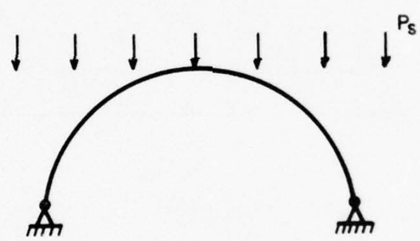
Sectional Forces from Dead Weight Loading

$$N_x = -g\ x/r\ (\ell-x)\ \sin\theta \qquad \text{(Eq B1)}$$

$$N_\theta = -ar\ \sin\theta \qquad \text{(Eq B2)}$$

$$1 = -a\ (\ell-2x)\ \cos\theta \qquad \text{(Eq B3)}$$

Snow Loading



$P_y = -P_s \sin\theta \cos\theta$

$P_z = \ P_s \sin^2\theta$

Where P_s is the snow load acting per unit area of the arch plan.

Sectional Forces from Snow Loading

$$N_x = P_s \frac{3x}{r}(\ell-x)(1-2\sin^2\theta) \qquad \text{(Eq B4)}$$

$$N_\theta = -P_s\ r \sin^2\theta \qquad \text{(Eq B5)}$$

$$T = -P_s(\ell/2-x)\ 3 \sin\theta \cos\theta \qquad \text{(Eq B6)}$$

Wind Load

$$P_z = P_w \cos\theta$$

Where p_w is the wind pressure acting on a surface normal to its direction.

Sectional Forces From Wind Load

$$N_x = -P_w(x/2r)(\ell-x)\cos\theta \qquad \text{(Eq B7)}$$

$$N_\theta = -P_w r \cos\theta \qquad \text{(Eq B8)}$$

$$T = P_w(\ell/2-x)\sin\theta \qquad \text{(Eq B9)}$$

Deflection Formula for Arch--Dead Weight and Uniform Load

(Refer to Figure B2)

$$\mu = -\sin\theta/Et\ \{w(L^2-4x^2/8(5L^2-4x^2/24R^2 + 4 + \nu) + wR^2\}*$$

Inserting the values L = 32 ft** and R = 13 ft, expanding and combining like terms,

$$\mu = -w\sin\theta/Et(0.000493x^4-0.50\nu x^2-2.7574x^2+128\nu+842.57) \qquad \text{(Eq B10)}$$

Where w is the combined dead and snow load.

SHOTCRETE ARCH ANALYSIS

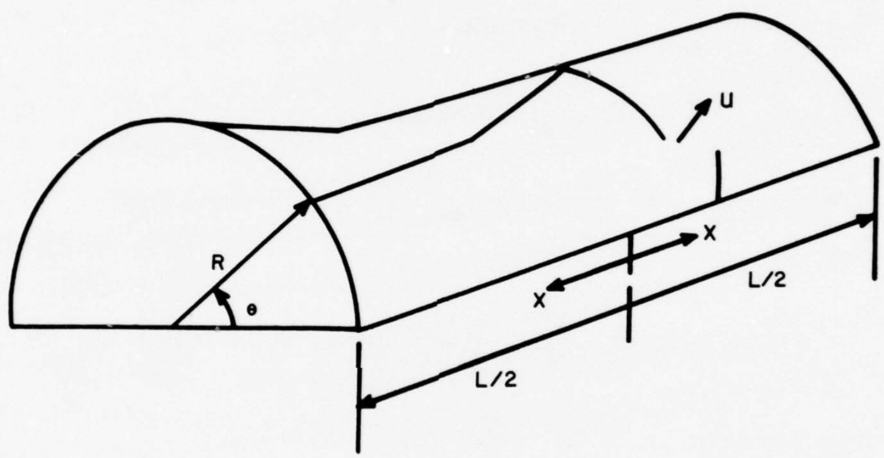
Dead Load

W_d = total dead weight of foam and shotcrete

Assume form thickness required, tf, is 6 in.

*W. Flugge, Stresses in Shells, Second Edition (Springer-Verlag, 1973), p. 125.

**Metric conversion factors: 1 in. = 25.4 mm; 1 ft = .3048 m; 1 lb/sq in. = 6.894 Pa.



u = radial displacement, R direction, plus outward

Figure B2. Sign convention for displacement due to dead weight loading.

Assume shotcrete thickness required, t_s, is 1 in.

W_{df} = dead weight of foam = (6/12) ft (2.5) lb/cu ft = 1.25 lb/sq ft

W_{ds} = dead weight of shotcrete = (1/12) ft (150) lb/cu ft = 12.5 lb/cu ft

$W_d = W_{df} + W_{ds}$ = 13.75 lb/sq ft

Snow Load

W_s = snow load = 15 lb/sq ft

Wind Load

W_w = wind load = 40 lb/sq ft

Equations B1 through B9 were used to construct Tables B1 through B3, which list shotcrete stresses resulting from applied loads at various locations on the arch.

Table B1a

Shotcrete Stress N_x/t_s Due to Load in lb/sq in.

X (ft)

Φ (deg)	0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	0.0	-8.5	-11.3	-8.5	0.0
34.51	0.0	-9.6	-12.8	-9.6	0.0
60	0.0	-14.7	-19.5	-14.7	0.0
90	0.0	-16.9	-22.6	-16.9	0.0

Stresses are symmetric about $\Phi = 90°$

Table B1b

Shotcrete Stress N_θ/t_s Due to Dead Load in lb/sq in.

X (ft)

Φ (deg)	0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
18.98	-4.8	-4.8	-4.8	-4.8	-4.8
30	-7.5	-7.5	-7.5	-7.5	-7.5
40	-9.6	-9.6	-9.6	-9.6	-9.6
60	-12.9	-12.9	-12.9	-12.9	-12.9
90	-14.9	-14.9	-14.9	-14.9	-14.9

Stresses are symmetric about $\Phi = 90°$

Table B1c

Shotcrete Stresses T/t_s Due to Dead Load in lb/sq in.

	X (ft)				
ϕ (deg)	0	8	16	24	32
0	-36.7	-18.3	0.0	18.3	36.7
30	-31.8	-15.9	0.0	15.9	31.8
45	-25.9	-13.0	0.0	13.0	25.9
55.49	-20.8	-10.4	0.0	10.4	20.8
60	-18.3	-9.2	0.0	9.2	18.3
90	0.0	0.0	0.0	0.0	0.0
120	18.3	9.2	0.0	-9.2	-18.3
124.51	20.8	10.4	0.0	-10.4	-20.8
135	25.9	13.0	0.0	-13.0	-25.9
150	31.8	15.9	0.0	-15.9	-31.8
180	36.7	18.3	0.0	-18.3	-36.7

Table B2a

Shotcrete Stresses N_x/t_s Due to Snow Load in lb/sq in.

	X (ft)				
ϕ (deg)	0	8	16	24	32
0	0.0	27.7	36.9	27.7	0.0
30	0.0	13.9	18.5	13.9	0.0
60	0.0	-13.9	-18.5	-13.9	0.0
90	0.0	-27.7	-36.9	-27.7	0.0
120	0.0	-13.9	-18.5	-13.9	0.0
150	0.0	13.9	18.5	13.9	0.0
180	0.0	27.7	36.9	27.7	0.0

Table B2b

Shotcrete Stress N_θ/t_s Due to Snow Load in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	-4.1	-4.1	-4.1	-4.1	-4.1
40	-6.7	-6.7	-6.7	-6.7	-6.7
60	-12.2	-12.2	-12.2	-12.2	-12.2
90	-16.3	-16.3	-16.3	-16.3	-16.3

Stresses are symmetric about ϕ = 90°

Table B2c

Shotcrete Stress T/t_s Due to Snow Load in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	-26.0	-13.0	0.0	13.0	26.0
45	-30.0	-15.0	0.0	15.0	30.0
60	-26.0	-13.0	0.0	13.0	26.0
90	0.0	0.0	0.0	0.0	0.0
120	26.0	13.0	0.0	-13.0	-26.0
135	30.0	15.0	0.0	-15.0	-30.0
150	26.0	13.0	0.0	-13.0	-26.0
180	0.0	0.0	0.0	0.0	0.0

Table B3a

Shotcrete Stress N_x/t_s Due to Wind Load in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	-24.6	-32.8	-24.6	0.0
30	0.0	-21.3	-28.4	-21.3	0.0
34.51	0.0	-20.3	-27.0	-20.3	
60	0.0	-12.3	-16.4	-12.3	0.0
90	0.0	0.0	0.0	0.0	0.0
120	0.0	12.3	16.4	12.3	0.0
145.49	0.0	20.3	27.0	20.3	0.0
150	0.0	21.3	28.4	21.3	0.0
180	0.0	24.6	32.8	24.6	0.0

Table B3b

Shotcrete Stress N_θ/t_s Due to Wind Load in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	-43.3	-43.3	-43.3	-43.3	-43.3
18.98	-41.0	-41.0	-41.0	-41.0	-41.0
30	-37.5	-37.5	-37.5	-37.5	-37.5
40	-33.2	-33.2	-33.2	-33.2	-33.2
60	-21.7	-21.7	-21.7	-21.7	-21.7
90	0.0	0.0	0.0	0.0	0.0
120	21.7	21.7	21.7	21.7	21.7
150	37.5	37.5	37.5	37.5	37.5
180	43.3	43.3	43.3	43.3	43.3

Table B3c

Shotcrete Stress T/t_s Due to Wind Load in lb/sq in.

Φ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	26.7	13.3	0.0	-13.3	-26.7
55.49	43.9	22.0	-22.0	-43.9	
60	46.2	23.1	0.0	-23.1	-46.2
90	53.3	26.7	0.0	-26.7	-53.3

Stresses are symmetric about $\Phi = 90°$

CHECK MAXIMUM STRESSES

Dead Load Only

N_x/t_s (max) = 0.0 < f_{ct} ok

N_x/t_s (min)(@x=16 ft, θ=90°) = -22.6 lb/sq in. < f_{cc} ok

N_θ/t_s (max) = 0.0, < f_{ct} ok

N_θ/t_s (min)(@x=16 ft, θ = 90°) = -14.9 lb/sq in. < f_{cc} ok

T/t_s (max)(@x=0, θ=180° and x=32 ft, θ=0°) = 36.7 lb/sq in. < f_c ok

T/t_s (min)(@x=0, θ=0° and x=32 ft θ=@80°) = -36.7 lb/sq in. < f_{cc} ok

Dead Load plus Snow Load

N_x/t_s (max)(@x=16 ft, θ=0 and x = 16 ft, $\theta\theta$=180°) = 36.9 lb/sq in. < f_{ct} ok

N_x/t_s (min)(@x=16 ft, θ=90°) = 59.5 lb/sq in. < f_{cc} ok

N_θ/t_s (max) = 0.0 < f_{ct} ok

N_θ/t_s (min)(@ any x, θ=90°) = -31.2 lb/sq in. < f_{cc} ok

T/t_s (max)(@x=32 ft, θ=45° and x=0, θ=135°) = 55.9 lb/sq in. < f_{cv} ok

T/t_s (min)(@x=0, θ=45° and x=32 ft, θ=135°) = -55.9 lb/sq in. < f_{cv} ok

Dead Load plus Wind Load

N_x/t_s (max)(@x=16 ft, θ=180°) = 32.8 lb/sq in. < f_{ct} ok

N_x/t_s (min)(@x=16 ft, θ=34.5°) = 39.8 lb/sq in. < f_{cc} ok

N_θ/t_s (max)(@ any x, θ=180°) = 43.3 lb/sq in. < f_{ct} ok

N_θ/t_s (min)(@ any x, θ=18.98°) = -45.8 lb/sq in. < f_{cc} ok

T/t_s (max)(@x=0, θ=124.5°) = 64.7 lb/sq in. < f_{cv} ok

T/t_s (min)(@x=23 ft, θ=124.5) = -64.7 lb sq/in. < f_{cv} ok

Dead Load plus Snow Load plus Wind Load

N_x/t_s (max)(@x=16 ft, θ=180°) = 69.7 lb/sq in. < f_{ct} ok

N_x/t_s (min)(@x=16 ft, θ=79°) = 62.6 lb/sq in. < f_{cc} ok

N_θ/t_s (max)(@ any x, θ=180°) = 43.3 lb/sq in. < f_{ct} ok

N_θ/t_s (min)(@ any x, θ=40°) = -49.5 lb/sq in. < f_{ct} ok

T/t_s (max)(@x=0, θ=130°) = 94.0 lb/sq in. < f_{cv} ok

T/t_s (min)(@x=32 ft, θ=130°) = -94.0 lb/sq in. < f_{cv} ok

A 1-in. thickness of steel fibrous shotcrete is adequate to carry the loads expected to be applied to the arch with the safety factors shown below.

Safety Factor

Safety Factor = SF = ultimate material stress/applied stress

Compression

SF = f_{cc}/N(min) = 62.6 lb/sq in. 6000 lb/sq in. = 96

Tension

SF = f_{ct}/N(max) = 900 lb/sq in./69.7 lb/sq in. = 13

Shear

SF = f_{cv}/T(max) = 1200 lb/sq in./94 lb/sq in. = 12.8

Since the 1-in. thickness of shotcrete is less than the 3 in. required for ballistics resistance, the ballistics resistance criteria control. The foam arch will be designed to carry 3 in. of shotcrete.

FOAM ARCH ANALYSIS--CONDITION 1

Dead Load

W_d = total dead weight of foam and shotcrete. Shotcrete thickness, t_s, is set at 3 in. Assume foam thickness, t_f, required is 4 in. and an SF of 1.5 is used to account for irregularity in foam thickness. The total foam thickness is 6 in. with only a 4 in. thickness assumed to carry the stress.

W_{df} = (6/12) ft (2.5) lb/cu ft = 1.25 lb/sq ft

W_{ds} = (3/12) ft (150) lb/cu ft = 37.5 lb/sq ft

W_d = W_{df} = 1.25 + 37.5 = 38.75 lb/sq ft

use W_d = 40 lb/sq ft

Wind Load

W_{sw} = 10 lb/sq ft

Equations B1 through B9 were used to construct Tables B4 and B5, which list foam stresses resulting from applied loads in Condition 1 on various locations on the arch.

Table B4a

Foam Stress N_x/t_s Due to Dead Load in Condition 1 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	0.0	-6.2	-8.2	-6.2	0.0
60	0.0	-10.7	-14.2	-10.7	0.0
83	0.0	-12.2	-16.3	-12.2	0.0
90	0.0	-12.3	-16.4	-12.3	0.0

Table B4b

Foam Stress N_θ/t_s Due to Dead Load in Condition 1 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	-5.5	-5.5	-5.5	-5.5	-5.5
60	-9.4	-9.4	-9.4	-9.4	-9.4
76	-10.5	-10.5	-10.5	-10.5	-10.5
90	-10.8	-10.8	-10.8	-10.8	-10.8

Table B4c

Foam Stress T/t_f Due to Dead Load in Condition 1 in lb/sq in.

X (ft)

Φ (deg)	0	8	16	24	32
0	-26.7	-13.3	0.0	13.3	16.7
30	-23.1	-11.6	0.0	11.6	23.1
60	-13.3	-6.7	0.0	6.7	13.3
90	0.0	0.0	0.0	0.0	0.0
120	13.3	6.7	0.0	-6.7	-13.3
150	23.1	11.6	0.0	-11.6	-23.1
173	26.5	13.2	0.0	-13.2	-26.5
180	26.7	13.3	0.0	-13.3	-26.7

Table B5a

Foam Stress N_x/t_f Due to Wind Load in Condition 1 in lb/sq in.

X (ft)

Φ (deg)	0	8	16	24	32
0	0.0	-1.5	-2.1	-1.5	0.0
30	0.0	-1.3	-1.8	-1.3	0.0
60	0.0	-0.8	-1.0	-0.8	0.0
83	0.0	-0.2	-0.3	-0.2	0.0
90	0.0	0.0	0.0	0.0	0.0
120	0.0	0.8	1.0	0.8	0.0
150	0.0	1.3	1.8	1.3	0.0
180	0.0	1.5	2.1	1.5	0.0

Table B5b

Foam Stress N_θ/t_f Due to Wind Load in Condition 1 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	-2.7	-2.7	-2.7	-2.7	-2.7
30	-2.3	-2.3	-2.3	-2.3	-2.3
60	-1.4	-1.4	-1.4	-1.4	-1.4
76	-0.7	-0.7	-0.7	-0.7	-0.7
90	0.0	0.0	0.0	0.0	0.0
120	1.4	1.4	1.4	1.4	1.4
150	2.3	2.3	2.3	2.3	2.3
180	2.7	2.7	2.7	2.7	2.7

Table B5c

Foam Stress T/t_f Due to Wind Load in Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
7	0.4	0.2	0.0	-0.2	-0.4
30	1.7	0.8	0.0	-0.8	-1.7
60	2.9	1.4	0.0	-1.4	-2.9
90	3.3	1.7	0.0	-1.7	-3.3

Stresses are symmetric about $\phi = 90°$

Check Maximum Stresses

Dead Load Only

N_x/t_f (max) = 0.0 < f_{ft} ok

N_x/t_f (min)(@x=15 ft, θ=90°) = -16.4 lb/sq in. < f_{fc} ok

N_θ/t_f (max) = 0.0 < f_{ft} ok

N_θ/t_f (min)(@ any x, θ=90°) = -10.8 lb/sq in. < f_{fc} ok

T/t_f (max)(@x=32 ft, θ=0° and x=0, θ=180°) = 26.7 lb/sq in. < f_{fv} ok

T/t_f (min)(@x=0, θ=0° and x=32 ft, θ=180°) = -26.7 lb/sq in. < f_{fv} ok

Dead Load and Wind Load

N_x/t_f (max)(@x=16 ft, θ=180°) = 2.1 lb/sq in. < f_{ft} ok

N_x/t_f (min)(@x=16 ft, θ=83°) = -16.6 lb/sq in. < f_{fc} ok

N_θ/t_f (max)(@ any x, θ=180°) = 2.7 lb/sq in. < f_{ft} ok

N_θ/t_f (min)(@ any x, θ=76°) = -11.2 lb/sq in. < f_{fc} ok

T/t_f (max)(@x=0, θ=173°) = 26.9 lb/sq in. < f_{fv} ok

T/t_f (min)(@x=32 ft, θ=173°) = -26.9 lb/sq in. < f_{fv} ok

A 4-in thickness of 2.5 lb/cu ft polyurethane foam is adequate to carry the loads expected to be applied to the arch under Condition 1 with the safety factors shown below.

Safety Factor

Compression

SF = f_{fc}/N(min) = 40 lb/sq in./16.6 lb/sq in. = 2.4

Tension

SF = F_{ft}/N(max) = 70 lb/sq in./2.7 lb/sq in. = 26

Shear

SF = f_{fv}/T(max) = 30 lb/sq in./26.9 lb/sq in. = 1.1

The low 1.1 SF for shear is justified because (1) the structure will not be occupied during the shotcrete operation, (2) the loading condition will not be permanent, and (3) the additional 2 in. of foam to be applied incorporates an extra safety factor.

Four inches of foam have been shown adequate for Condition 1. Condition 2 must now be checked.

FOAM ARCH ANALYSIS--CONDITION 2

Dead Load

The shotcrete dead load is not included because it will be applied only during construction, which was checked in Condition 1.

Assume a foam thickness, t_f, of 4 in. to carry stress but 6 in. to compute the dead load.

W_{df} = (6/12) ft (2.5) lb/cu ft = 1.25 lb/sq ft

$W_{ds} = 0$

$W_d = W_{df} + W_{ds}$ = 1.25 lb/sq ft

Snow Load

W_s = snow load = 15 lb/sq ft

Wind Load

W_{sw} = wind load = 40 lb/sq ft

Equations B1 through B9 were used to construct Tables B6 through B8, which list foam stresses resulting from the applied loads in Condition 2 at various locations on the arch.

Table B6a

Foam Stress $N_x t_f$ Due to Dead Load in Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
3.5	0.0	-0.02	-0.03	-0.2	0.0
30	0.0	-0.2	-0.3	-0.2	0.0
60	0.0	-0.3	-0.4	-0.3	0.0
75	0.0	-0.4	-0.5	-0.4	0.0
90	0.0	-0.4	-0.5	-0.4	0.0

Stresses are symmetric about $\phi = 90°$

Table B6b

Foam Stress N_θ/t_f Due to Dead Load in Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
1.5	-0.0	-0.0	-0.0	-0.0	-0.0
5	-0.03	-0.03	-0.03	-0.03	-0.03
30	-0.2	-0.2	-0.2	-0.2	-0.2
60	-0.3	-0.3	-0.3	-0.3	-0.3
90	-.03	-0.3	-0.3	-0.3	-0.3

Table B6c

Foam Stress T/t_f Due to Dead Load in Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	-0.8	-0.4	0.0	0.4	0.8
30	-0.7	-0.4	0.0	0.4	0.8
43.6	-0.6	-0.3	0.0	0.3	0.6
60	-0.6	-0.2	0.0	0.2	0.4
90	0.0	0.0	0.0	0.0	0.0
120	0.4	0.2	0.0	-0.2	-0.4
136.4	0.6	0.3	0.0	-0.3	-0.6
150	0.7	0.4	0.0	-0.4	-0.7
180	0.8	0.4	0.0	-0.4	-0.8

Table B7a

Foam Stress N_x/t_f Due to Snow Load in Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	6.9	9.2	6.9	0.0
30	0.0	3.5	4.6	3.5	0.0
60	0.0	-3.5	-4.6	-3.5	0.0
75	0.0	-6.0	-8.0	-6.0	
90	0.0	-6.9	-9.2	-6.9	0.0
120	0.0	-3.5	-4.6	-3.5	0.0
150	0.0	3.5	4.6	3.5	0.0
180	0.0	6.9	9.2	6.9	0.0

Table B7b

Foam Stress N_θ/t_f Due to Snow Load in Condition 2 in lb/sq in.

Φ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
5	-0.03	-0.03	-0.03	-0.03	-0.03
30	-1.0	-1.0	-1.0	-1.0	-1.0
60	-3.0	-3.0	-3.0	-3.0	-3.0
90	-4.1	-4.1	-4.1	-4.1	-4.1

Stresses are symmetric about $\Phi = 90°$

Table B7c

Foam Stress T/t_f Due to Snow Load in Condition 2 in lb/sq in.

Φ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	-6.5	-3.3	0.0	3.3	6.5
43.6	-7.5	-3.3	0.0	3.3	7.5
45	-7.5	-3.8	0.0	3.3	7.5
60	-6.5	-3.3	0.0	3.3	6.5
90	0.0	0.0	0.0	0.0	0.0
120	6.5	3.3	0.0	-3.3	-6.5
135	7.5	3.8	0.0	-3.8	-7.5
136.4	7.5	3.3	0.0	-3.3	-6.5
150	6.5	3.3	0.0	-3.3	-6.5
180	0.0	0.0	0.0	0.0	0.0

Table B8a

Foam Stress N_x/t_f Due to Wind Load in Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
3.5°	0.0	-6.2	-8.2	-6.2	0.0
30	0.0	-5.3	-7.1	-5.3	0.0
60	0.0	-3.1	-4.1	-3.1	0.0
75	0.0	-1.6	-2.1	-1.6	0.0
90	0.0	-1.6	-2.1	-1.6	0.0
120	0.0	3.1	4.1	3.1	0.0
150	0.0	5.3	7.1	5.3	0.0
180	0.0	6.2	8.2	6.2	0.0

Table B8b

Foam Stress N_θ/t_f Due to Wind Load Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	-10.8	-10.8	-10.8	-10.8	-10.8
1.8°	-10.8	-10.8	-10.8	-10.8	10.8
30	-9.4	-9.4	-9.4	-9.4	-9.4
60	-5.4	-5.4	-5.4	-5.4	-5.4
90	0.0	0.0	0.0	0.0	0.0
120	5.4	5.4	5.4	5.4	5.4
150	9.4	9.4	9.4	9.4	9.4
180	10.8	10.8	10.8	10.8	10.8

Table B8c

Foam Stress T/t_f Due to Wind Load in Condition 2 in lb/sq in.

ϕ (deg)	X (ft) 0	8	16	24	32
0	0.0	0.0	0.0	0.0	0.0
30	6.7	3.3	0.0	-3.32	-6.7
60	11.6	5.8	0.0	-5.8	-11.6
90	13.3	6.7	0.0	-6.7	-13.3

Stresses are symmetric about $\phi = 90°$

Check Maximum Stresses

Dead Load Only

Stresses are negligible. Dead load only in Condition 1 is much more severe and has been checked.

Dead Load and Snow Load

N_x/t_f (max)(@x=16 ft, θ=0° and x=16 ft, θ=180°) = 9.2 lb/sq in. $< f_{ft}$ ok

N_x/t_f (min)(@x=16 ft, θ=90°) = -9.7 lb/sq in. $< f_{fc}$ ok

N_θ/t_f (max) = 0.0

N_θ/t_f (min)(@x=16 ft, θ=90°) = 4.4 lb/sq in. $< f_{fc}$ ok

T/t_f (max)(@x=32 ft, θ=43.6° and x=0, θ=136.4°) = 8.1 lb/sq in $< f_{fv}$ ok

T/t_f (min)(@x=0, θ=43.6° and x=32 ft, θ=136.4°) = -8.1 lb/sq in. $< f_{fv}$ ok

Dead Load and Wind Load

N_x/t_f (max)(x=16 ft, θ=180°) = 8.2 lb/sq in. $< f_{ft}$ ok

N_x/t_f (min)(x=16 ft, θ=3.5°) = -8.5 lb/sq in. $< f_{fc}$ ok

N_θ/t_f (max)(@ any x, θ=180°) = 10.8 lb/sq in. $< f_{ft}$ ok

N_θ/t_f (min)(@ any x, θ=1.5°) = -10.8 lb/sq in. $< f_{fc}$ ok

T/t_f (max)(@x=0, θ=180°) = 14.1 lb/sq in. $< f_{fv}$ ok

T/t_f (min)(@ax=32 ft. θ=180°) = -14.1 lb/sq in. $> f_{fv}$ ok

Dead Load and Snow Load and Wind Load

N_x/t_f (max)(@x=16 ft, θ=180°) = 17.4 lb/sq in. $> f_{ft}$ ok

N_x/t_f (min)(@x=16 ft, θ=75°) = -10.6 lb/sq in. $> f_{fc}$ ok

N_θ/t_f (max)(@ any x, θ=180°) = 10.8 lb/sq in. $> f_{ft}$ ok

N_θ/t_f (min)(@ any x, θ=5°) = -10.9 lb/sq in. $> f_{fc}$ ok

T/t_f (max)(@x=0, θ=122°) = 18.5 lb/sq in. $> f_{fv}$ ok

T/t_f (min)(@x=32 ft, θ=122°) = -18.5 lb/sq in. $> f_{fv}$ ok

A 4-in. thickness of 2.5 lb/cu ft polyurethane foam is adequate to carry the loads expected to be applied to the arch under Condition 2 with the safety factors shown below.

Safety Factor

Compression

$SF = f_{fc}/N(min) = 40$ lb/sq in./10.8 lb/sq in. = 3.7

Tension

$SF = f_{ft}/N(max) = 70$ lb/sq in./17.4 lb/sq in. = 4.0

Shear

$SF = f_{fv}/T(max) = 30$ lb/sq in./18.5 lb/sq in. = 1.6

DEFLECTIONS

Foam Arch--Dead Load Only

$$w = 1.25 \text{ lb/sq in.}$$

From Equation B10, Table B9 lists the deflection, μ, at various points on the arch. (Refer to Figure B2.)

Shotcrete Arch Dead Load Foam Plus Dead Load 3 In. Shotcrete

$$w = 1.75 + 37.5 = 38.75 \text{ lb/sq ft use 40 lb/sq ft}$$

Deflections are symmetric about $\theta=90°$ and $x=0$. A 10-in. deflection, although somewhat excessive, should not damage the arch or its interior (Table B10).

Shotcrete Arch--Dead Load of 3 In. Shotcrete Plus 6 In. Foam Plus Snow Load

$$w = 40 + 15 = 55 \text{ lb/sq ft (Table B11).}$$

Table B9

Foam Deflection μ Due to Foam Dead Weight in Inches

Φ (deg)	X (ft) 0	8	16
0	0	0	0
30	0.16	-0.12	-0.03
60	-0.27	-0.21	-0.05
90	-0.31	-0.25	-0.06

Deflections are symmetric about $\Phi = 90°$ and $x = 0$.

Table B10

Foam Deflection μ Due to Foam and Shotcrete Dead Weight in Inches

Φ (deg)	X (ft) 0	8	16
0	0	0	0
30	-5.0	-3.9	-1.0
60	-8.6	-6.8	-1.7
90	-10.0	-7.9	-2.0

Deflections are symmetric about 0 $\Phi = 90°$ and $x = 0$.

Table B11

Shotcrete Deflection μ Due to Foam and Shotcrete Dead Weight plus Snow in Inches

Φ (deg)	X (ft) 0	8	16
0	0	0	0
30	-0.002	-0.002	-0.0
60	-0.004	-0.003	-0.0
90	-0.005	-0.004	-0.0

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